CRYSTALLINE-SILICON RELIABILITY LESSONS FOR THIN-FILM MODULES*

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ABSTRACT

Key reliability and engineering lessons learned from the 10-year history of the Jet Propulsion Laboratory's Flat-Plate Solar Array Project are presented and analyzed. Particular emphasis is placed on lessons applicable to the evolving new thin-film cell and module technologies and the organizations involved with these technologies. The user-specific demand for reliability is a strong function of the application, its location, and its expected duration. Lessons relative to effective means of specifying reliability are described, and commonly used test requirements are assessed from the standpoint of which are the most troublesome to pass, and which correlate best with field experience. Module design lessons are also summarized, including the significance of the most frequently encountered failure mechanisms and the role of encapsulant and cell reliability in determining module reliability. Lessons pertaining to research, design, and test approaches include the historical role and usefulness of qualification tests and field tests.

INTRODUCTION

During the past 10 years the reliability of crystalline-silicon modules has been brought to a high level with lifetimes approaching 20 years, and excellent industry credibility and user satisfaction. With the emergence of thin-film power modules it is important to review the lessons learned from the crystalline-Si product development history and apply the technology base, where applicable, to enhance the development of thin-film modules.

The transition from crystalline modules to thin-film modules is comparable to the transition from discrete transistors to integrated circuits. New cell materials and monolithic structures will require new device processing techniques, but the package function and design will evolve to a lesser extent. Although there may be new encapsulants optimized to take advantage of the mechanical flexibility and low-temperature processing features of thin films, the reliability and life-degradation stresses and mechanisms will remain mostly unchanged. Key reliability technologies in common between crystalline and thin-film modules include hot-spot heating, galvanic and electrochemical corrosion, hail-impact stresses, glass breakage, mechanical fatigue, photothermal degradation of encapsulants, operating temperature, moisture sorption, circuit design strategies, product safety issues, and the process required to achieve a reliable product from a laboratory prototype.

Increased array life and reliability directly influence the economic viability of photovoltaics as an energy source by controlling the total number and size of revenue payments received from future sales of electricity. After considerations of present-value discounting and escalation of the worth of electricity in future years, a 30-year PV plant, for example, is worth 25 to 30 percent more than a 20-year-life plant. Based on this economic sensitivity to plant life, a 30-year life was chosen as the target of the crystalline-Si module development effort. To achieve this high level of reliability, a comprehensive reliability program was undertaken in 1975 by the Jet Propulsion Laboratory Flat-Plate Solar Array (FSA) Project to develop the technology base required.

The remainder of this paper summarizes the key reliability lessons learned from this 10-year crystalline-Si module development history with particular emphasis on lessons of use to new technologies and companies. For convenience the lessons are divided into three topic areas: Reliability Requirement Lessons, Reliability Design Lessons, and Reliability Testing Lessons.

RELIABILITY REQUIREMENT LESSONS

One element of controversy that enters early into the debate about reliability is the trade-off

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* This paper presents the results of one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy, through an agreement with the National Aeronautics and Space Administration.

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Proceedings of the 18th IEEE Photovoltaic Specialists Conference
Las Vegas, Nevada, October 21-25, 1985

between designing a high-reliability, long-life product versus an inexpensive, replaceable product. There is no easy answer to this question, for it involves manufacturer and user-specific considerations. The approach taken in the FSA Project was to develop the technologies for a long-life product, including the life-prediction and life-cycle costing economic tools to allow each manufacturer and user to best evaluate his needs.

Manufacture- and user-specific considerations include such items as the service environment and the expected duration of the intended application, expected future cost reductions or product obsolescence, the ease and cost of periodic maintenance and replacement, and the consistency of the product's reliability with the manufacturer's image and reputation.

Among these, probably the most fundamental element defining reliability requirements is the level of applied stresses in the intended application. Experience with crystalline-silicon modules suggests the following environments play the key role (ordered from most significant to least):

(1) System operating voltage
(2) Operating temperature
(3) Ambient humidity level
(4) Ambient soiling level
(5) Presence of salt fog (marine environments)
(6) Level of solar exposure (ultraviolet)
(7) Maximum hail stone impact
(8) Maximum wind velocity (structural loading)

System voltage heads the list because it impacts a large number of reliability parameters including voltage isolation and grounding requirements, electrochemical corrosion, hot-spot heating, bypass diodes, and the number of series cells in an array source circuit. Since the number of series cells affects the array's tolerance to open-circuit cell failures, system voltage indirectly influences the tolerance of the array to cracked cells and interconnect open circuits (1).

Operating temperature also shares the top of the list by having an accelerating influence on nearly every failure mechanism including voltage isolation, corrosion, hot-spot heating, photothermal degradation of encapsulants, delamination, interconnect fatigue, and cell cracking. All but the last two mechanisms typically have an Arrhenius dependency on temperature (log reaction rate inversely proportioned to reciprocal absolute temperature) with a reaction rate doubling for approximately every 10°C increase in temperature (2,3,4). This implies that an application that operates 10°C hotter than another will last only half as long. Interconnect fatigue and cell cracking are sensitive to differential expansion stresses caused by the number of temperature cycles (1,5) and the high and low temperature extremes.

Humidity, like temperature, has a strong accelerating influence on many of the degradation mechanisms including corrosion, voltage breakdown, photothermal degradation and delamination (2,3). Humidity can also lead to large differential expansion stresses that aggravate delamination and fatigue.

The remaining environments are similarly site specific and have been found to have lesser, but important influences on module reliability (1).

Quantifying Application Stress Requirements

Once the important application-dependent and site-dependent stresses are identified, a key difficulty is reducing them to specific stress-time requirements against which the module can be designed and verified. Some environments, such as system voltage level, are easily identified; others such as hail stone size, temperature and humidity extremes, and maximum wind velocity, require reference to historical weather data and considerations of statistical likelihood over the period of the intended application. In general, two types of stress-time requirements have been found useful: (1) a statement of the actual site-application requirement (such as 30 years of the operating temperatures of a Boston roof-mounted array), and (2) an accelerated qualification test against which the module can be tested.

The site-application requirement is needed for detailed life-prediction simulation analyses and is generally computed based on SOLMET hourly weather histories for sites in the United States (6,7). For example, time-varying module temperature and humidity level can be computed from the hourly weather data using heat transfer and water-sorption models that include the application thermal boundary conditions. This results in an analytical model of the application stress-time requirement.

Although the analytical stress-time model is very useful in life prediction computer simulations, it fails to provide a requirement that a fabricated module can be quickly and inexpensively tested to; this need is met by a qualification test. Ideally the qual test stress-time level is selected to correlate to a given application stress-time environment; certainly this is the desired goal. In practice, the stress profile of a given qual test is carefully iterated based on analytical predictions and field aging experience to provide a best possible correlation.

During the 10 years of the FSA Project, a number of module qualification tests have been developed and refined to the present Block V sequence detailed in Table 1 (8). These test levels have been carefully selected and revised with time so as to fail past module designs with a known history of field problems and to pass modules with good field performance (9). A review of the experience with these tests provides important lessons for designers of future thin-film modules.

Temperature Cycling and Humidity Cycling. Consistent with their importance as key accelerators of degradation mechanisms, the temperature and humidity tests serve as the

Table 1. JPL Block V Module Qualification Tests

Test	Level and Duration
Temperature cycling	200 cycles; each cycle: 4 h, −40°C to +90°C
Humidity-freeze	10 cycles; each cycle: 20 h at 85°C, 85% RH followed by 4 h excursion to −40°C
Cyclic pressure loading	10000 cycles, ± 2400 Pa (± 50 lb/ft^2)
Wind resistance (shingles only)	Underwriters Lab Standard UL 997 1.7 k Pa (35 lb/ft^2)
Hail impact	10 impacts at most sensitive locations using 25.4 mm (1 in.) iceball at 23.2 m/sec (52 mph)
Electrical isolation	Leakage current ≤50 μA at twice worst-case system open circuit voltage plus 1000 V
Hot-spot endurance	3 cells back-biased to maximum bypass-diode voltage and cell-string current for 100 h of on-time

workhorse requirements in the qual test sequence; they have good correlation to field failures and are generally the most difficult to pass. Typical failure mechanisms include encapsulant delamination, interconnect fatigue, cracked cells, cell metallization corrosion and warping of plastic parts. The 85°C and 90°C upper temperature limits of these tests accurately reflect upper-bound field operating temperatures, and the -40°C lows reflect ambient lows. Thin-film modules should be monitored for failures caused by differential expansion and corrosion such as delamination of encapsulants, loss of cell metallization, and degradation of monolithic cell interconnects.

Hot-Spot Testing. The need for hot-spot testing is principally associated with high-voltage applications, which can generate substantial reverse voltages across a temporarily shadowed cell or module, and thereby result in damaging hot-spot heating levels. The complexity of the hot-spot heating phenomenon requires that a number of cell and module parameters be properly accounted for during testing, and has resulted in a carefully defined test procedure (8). The test is generally easy to meet if generic bypass diode recommendations are followed, such as those recently developed for amorphous-silicon modules (10).

Mechanical Loading, Twist and Hail Tests. These tests define generic mechanical-loading stress levels for modules, and are applicable for most applications including extreme-climate (mountain top) applications. The tests account for wind, snow and ice loads, module mounting to non-planar support structures, and impact by hail stones of 2-cm diameter and less. They are effective design requirements and generally straightforward to meet with 3-mm (1/8-inch) tempered-glass module designs. Annealed glass may pass these tests, but often exhibits excessive numbers of field failures from thermal stresses encountered due to non-uniform solar heating of the module area. Applications with a significant incidence of large (>2-cm diameter) hail stones may choose to design for a greater resistance to hail impact; 5-mm (3/16-inch) tempered glass is generally the thickest used, and is adequate for 5-cm diameter hailstones.

Voltage Standoff (Hipot) Testing. This requirement is for modules intended for use in applications with system voltages above 50 v. It requires great care in the design of the module's electrical insulation system and is troublesome to meet. Typical problems include excessive leakage current through partially conductive gaskets and edge seals, and inadequately insulated electrical leads. It may pose special problems for thin-film modules made with tin-oxide coated glass because the edge of the glass is often electrically connected to the cells through the conductive oxide.

In addition to these Block V Qualification tests, there are a few key environmental requirements that have not been reduced to a qual test, or have only recently been. These include photothermal aging, soiling, electrochemical corrosion, and overheating of bypass diodes.

Photothermal Aging. In crystalline-silicon modules, this requirement addresses the resistance of module encapsulants to ultraviolet photothermal oxidation. Although long-term life-testing methods have been evaluated, the complex dependency of photodegradation on spectral irradiance, temperature, and humidity level has precluded the definition of a short-term qualification test with good field correlation. Most crystalline modules have met the requirement by using materials such as glass, silicon ribbon, and ethylene-vinyl-acetate (EVA) with proven UV stability (11). Modules incorporating other polymers in their construction must be carefully evaluated using long-term testing techniques that assess gradual loss of UV screens and antioxidants as well as test the basic photothermal stability of the as-fabricated module. Outdoor testing at fixed elevated temperatures such as 85°C is proving increasingly useful in this regard. In addition to testing the photothermal stability of the polymers, this type of test may also be useful to assess light-induced effects in thin-film modules such as amorphous silicon.

Soiling. Front surface soiling by airborne contaminants can lead to significant degradation of module performance in cases where the illuminated surface is a polymer material. As with photothermal oxidation, no short-term qual test has proven reliable, but material selection guidelines and soil-resistant coatings have been developed based on long-term field tests (12). Glass has proven to be an excellent low-soiling surface.

Electrochemical Corrosion. The only qual test currently related to system operating voltage is the hipot test. An important additional degradation mechanism is accelerated corrosion of the solar-cell materials due to voltage-induced ionic migration between cells and the module frame. Although no short-term qual test exists, research on this mechanism is progressing rapidly and has led to preliminary design guidelines and testing methods (13).

Bypass Diode Overheating. Insufficient heat sinking and excessive current levels are the primary causes of bypass diode failures. A new qual test has been developed to define and verify acceptable bypass diode thermal design and implementation (14). The requirement limits the diode junction temperature under hot field conditions (100 mW/cm^2, 40°C ambient) to 50°C below the diode manufacture's stated maximum allowable junction temperature.

RELIABILITY DESIGN LESSONS

A large number of design techniques and analysis methods have been developed during the past 10 years to assist in meeting the above described requirements with crystalline-Si solar cells. In lieu of repeating previous reviews of these technologies (1,15), it is useful to examine some of the more fundamental lessons of the design experience.

Identification of Key Reliability Problem Areas.

One of the more intriguing and recurring issues in module design is the relative role of the module encapsulant system in achieving module reliability by protecting fragile solar cells. After 10 years of testing both bare cells and modules, it is becoming clear that the encapsulant is the most problem- prone part of the module, and it generally does not enhance the reliability of the solar cells over their performance unencapsulated. For example, in tests at Clemson University, bare crystalline-Si cells have routinely demonstrated better reliability than the same cells when encapsulated in any of a variety of typical photovoltaic encapsulant systems (16). The principal demonstrated function of the encapsulant is to structurally support the cells and isolate them electrically for safety reasons. Secondary functions include providing an easily cleaned external surface and reducing the cell operating temperature by increasing the surface emissivities.

Unfortunately, while attempting to provide these functions, the module encapsulant often aggravates or creates a number of failure mechanisms. These include cracking, yellowing, delamination, accelerated corrosion, and lamination (processing), and differential expansion stresses. In addition, the encapsulant may fail to perform its intended function, resulting in voltage breakdown, excessive leakage currents, increased soiling or increased operating temperatures. The conclusion is that cells must be chosen with good inherent reliability, and the encapsulant must be carefully selected to perform its functions while not degrading the reliability and efficiency of the unencapsulated cells.

Aside from failures associated with the encapsulant, the part of a crystalline-Si module second most likely to have a failure is the electrical circuit. This includes solar cell electrical interconnects and solder joints, bus wires, and electrical terminal components.

Typical failures include mechanical fatigue of conductors, broken solder joints, corrosion of electrical terminals, photothermal degradation of connectors and cabling, and thermal warping of junction boxes.

The most reliable element of a crystalline-Si module is often the cells themselves. Although cell reliability problems are infrequent in modern crystalline-Si modules, historical failure mechanisms include cell cracking, metallization delamination (increased series resistance), and degradation of the anti-reflective coating. This demonstrated high reliability with crystalline-Si cells may or may not be achievable with thin-film cells; establishing the inherent reliability of a candidate thin-film cell is therefore an important first step in the process of achieving a high-reliability long-life module. Life testing of bare cells provides an effective means of evaluating cell reliability and providing a baseline for comparison with post-encapsulation reliability data.

Establishment of Mechanism-Specific Reliability Goals.

A key step in achieving high reliability is establishing mechanism-specific reliability goals. This forces several disciplines on the design process: First, it requires that all failure mechanisms be determined, and that the economic importance at the system level be determined for each failure or degradation occurence. For some mechanisms, such as encapsulant soiling, the economic impact is directly proportional to the degradation level and is easily calculated. For others, such as open-circuit or short-circuit failures of individual solar cells, elaborate statistical-economic analyses that include the effects of circuit redundancy, maintenance practices, and life-cycle costing are required (1, 5). Without such analyses, failure levels cannot be interpreted with meaning.

Table 2 lists the 13 principal failure mechanisms for flat-plate crystalline-Si photovoltaic modules, together with their economic significance (1). The units of degradation listed in the third column provide a convenient means of quantifying the failure levels of the individual mechanisms according to their approximate time dependence. For example, units of %/yr in the context of component or module failures reflect a constant percentage of components failing each year. For components that fail with increasing rapidity, (%/y^2) is the unit used to indicate linearly increasing failure rate. For those mechanisms classified under power degradation, the %/yr units refer to the percentage of power reduction each year.

Using the units described above, Columns 4 and 5 of Table 2 indicate the level of degradation for each mechanism that will result in a 10% increase in the cost of delivered energy from a large PV system. Because the mechanisms will generally occur concurrently, the total cost impact is the

Table 2. System Life-cycle Energy Cost Impact and Allowable Degradation Levels for 13 Principal Crystalline-Silicon Module Failure Mechanisms

Type of Degradation	Failure Mechanism	Units of Degrad.	Level for 10% Energy Cost Increase*		Allocation for 30-year Life Module	Economic Penalty
			k = 0	k = 10		
Component failures	Open-circuit cracked cells	%/yr	0.08	0.13	0.005	Energy
	Short-circuit cells	%/yr	0.24	0.40	0.050	Energy
	Interconnect open circuits	%/yr²	0.05	0.25	0.001	Energy
Power degradation	Cell gradual power loss	%/yr	0.67	1.15	0.20	Energy
	Module optical degradation	%/yr	0.67	1.15	0.20	Energy
	Front surface soiling	%	10	10	3	Energy
Module failures	Module glass breakage	%/yr	0.33	1.10	0.1	O&M
	Module open circuits	%/yr	0.33	1.10	0.1	O&M
	Module hot-spot failures	%/yr	0.33	1.10	0.1	O&M
	By-pass diode failures	%/yr	0.70	2.40	0.05	O&M
	Module shorts to ground	%/yr²	0.022	0.122	0.01	O&M
	Module delamination	%/yr²	0.022	0.122	0.01	O&M
Life-limiting wearout	Encapsulant failure due to loss of stabilizers	Years of life	27	20	35	End of life

*k = Discount rate

Table 3. System Life-Cycle Energy Cost Impact and Allowable Degradation Levels for 13 Principal Thin-Film Module Failure Mechanisms

Type of Degradation	Failure Mechanism	Units of Degrad.	Level for 10% Energy Cost Increase*		Allocation for 30-Year Life Module	Economic Penalty
			k = 0	k = 10		
Component failures	Open-circuit between cells	%/yr	0.08	0.13	0.02	Energy
	Short-circuit cells	%/yr	0.24	0.40	0.05	Energy
Power degradation	Light induced effects	%	10	10	5	Energy
	Cell gradual power loss	%/yr	0.67	1.15	0.20	Energy
	Module optical degradation	%/yr	0.67	1.15	0.02	Energy
	Front surface soiling	%	10	10	3	Energy
Module failures	Module glass breakage	%/yr	0.33	1.10	0.1	O&M
	Module open circuits	%/yr	0.33	1.10	0.1	O&M
	Module hot-spot failures	%/yr	0.33	1.10	0.1	O&M
	Bypass diode failures	%/yr	0.70	2.40	0.05	O&M
	Module shorts to ground	%/yr²	0.022	0.122	0.01	O&M
	Module delamination	%/yr²	0.022	0.122	0.01	O&M
Life-limiting wearout	Encapsulant failure due to loss of stabilizers	Years of life	27	20	35	End of life

*k = Discount rate

sum of the 13 cost contributions. Column 6 lists a strawman allocation of allowable degradation among the 13 mechanisms to achieve a specific total reliability performance. In this case the reliability allocations are consistent with a 20% increase in the cost of energy over that from a perfect, failure-free system with a 30-year life.

In contrast to Table 2, Table 3 provides similar data for 13 likely failure mechanisms associated with modules made with thin-film cells monolithically deposited on a glass superstrate. Note that the module-failure and power-degradation mechanisms remain essentially the same except for module optical degradation and light induced effects. Because the thin-film cells are assumed deposited directly on the glass superstrate, there is no polymer in the optical path to the cell that can degrade in its transmission properties; the allocation for this mechanism is therefore substantially reduced. In its place is the new, and probably larger power degradation mechanism referred to as light-induced effects. The 5% allocation for this degradation assumes it reaches equilibrium quickly in the first few months of field application and remains constant at the 5% level over the plant life.

Another important difference with monolithic thin-film modules is the absence of cell cracking and mechanical fatigue of the leads that interconnect crystalline-Si cells. Unfortunately, these failure mechanisms, which have been successfully addressed through circuit redundancy features in crystalline-Si modules, are replaced with open-circuiting of the monolithic cell interconnect in thin-film modules.

This mechanism has already taken its toll in amorphous-Si field installations and demands careful attention. Notice from Column 4 of Table 3 that one interconnect failure per thousand cells per year causes the cost of generated electricity to increase by 10%; this assumes extensive series paralleling and the use of bypass diodes to minimize the impact of cell open circuits (1).

A third mechanism category of importance to thin-film modules includes a variety of mechanisms responsible for gradual, but continuing degradation of the cell power. Examples include losses caused by migration of elements into and among the cell's thin-film layers, corrosion of the rear metallization, increased series resistance of cell interconnects, and localized shunting of cell areas. Although the allocation for this mechanism category has been left at 0.2% per year, early reliability data indicate that this could be a challenging target for thin-film modules.

Although different degradation allocations could have been chosen in Tables 2 and 3, the important point is that these allocations allow the significance of observed failures to be measured, and goals to be developed to guide mechanism-specific research activities.

RELIABILITY TESTING LESSONS

Because the physics of most failure mechanisms is poorly understood, achieving high reliability requires a strong reliance on empirical characterization and testing. This can take the form of laboratory accelerated tests, outdoor test racks, or complete system application experiments. Each has its lessons.

Laboratory Testing.

At the root of achieving long-life modules is ensuring that all the important problems are identified early so that they can be systematically addressed. The qualification tests described earlier (Table I) have been found to be the most cost-effective way to identify obvious reliability problems, and should be applied as early in the design process as possible using prototype hardware manufactured with candidate materials and processes. Even with careful attention to the lessons of the past, new module designs almost never pass the qual tests on the first try.

In addition to the qual tests, it is important to conduct long-term life tests at parametric stress levels to achieve a quantitative understanding of the parameter dependencies involved with complex failure mechanisms. Photothermal aging and corrosion of cells and modules are obvious examples. Because of the expense and many months required, this type of testing must generally proceed systematically as part of an integrated research effort, as opposed to being a part of a short-term product development cycle.

Outdoor Test Racks.

A second testing approach requiring extended test durations is outdoor testing on field test racks. Unfortunately, the correlation between this type of testing and observed failures in field applications has historically been poor. Key problems stem from the limited number of samples on test, and the absence of many user-interface stresses such as applied voltages. This type of testing is mostly useful for backing up the qual tests, to catch a not-tested-for mechanism that might become visible after a modest period of field aging. The tests can be enhanced substantially by incorporating as many user-interface stresses as possible and increasing the number of samples on test to a maximum. Important user-interface stresses include module operating point (open circuit, maximum power point, and short circuit), array voltage biasing of the cell string above and below the module-frame ground potential, partial shadows, and increased operating temperatures.

Forcing a constant, but reasonable operating temperature such as 85°C or 100°C can be an effective way to accelerate certain field aging mechanisms in a predictable way. One means of achieving the increased temperature is with thermostatically controlled external heaters, which are cycled off at night. Simultaneous testing at two separate temperatures allows determination of the degradation-rate temperature dependence and therefore provides improved extrapolation of degradation data to nominal field conditions.

Application Experiments.

Because of the shortcomings of laboratory and test-rack aging, many problems are not acknowledged as such until they are encountered in a large operating system. The large number of modules involved in such systems is extremely useful in quantifying the significance of the problem, and the user-interface stresses are real. One failure out of 10 in a qualification test, or in a field test rack, is often discounted as a curiosity; 10% failures in a large system is a problem.

Because of the often-present desire to field a large high-visibility application as soon as possible, there is great pressure to shortcut the laboratory-testing and design-qualification process, and to go directly to the field. This almost always results in tarnished reputations, slipped schedules, minimal learning, cost overruns, and early application retirement. The high cost of failure in the field, together with the need for field testing argues for careful laboratory testing and test-rack aging, followed by thoughtful selection of a low-risk first field application. This system should be instrumented to obtain quantitative data on failures, and be designed with failure containment features and failure contingency plans.

Failure Analysis.

Aside from the testing method used to identify a reliability problem, a thorough and careful failure analysis is a critical next step. It is not sufficient to know that a module open-circuited; one must determine where and why in order to effect a corrective action. Did an interconnect fatigue due to a faulty design, or did someone forget to solder a lead to a solar cell? The correct response is critically dependent on understanding the true source of the problem.

SUMMARY REMARKS

Achieving 30-year-life flat-plate PV modules requires a systematic approach to the identification of failure mechanisms, to the establishment of allowable failure levels, to the development of reliability design and test methods, and to the definition of cost-effective solutions. Based on this methodology, the reliability of flat-plate crystalline-Si PV modules has steadily increased from 5-year-life modules of the early 1970s to 10- to 20-year-life modules of today. It is expected that thin-film modules will have much in common with their crystalline precursors and will be able to make substantial use of the reliability design and test methods developed to date. At the same time, however, new materials and processes in thin-film modules will require a diligent reliability program involving evaluation, testing, and the development of new solution techniques unique to the attributes and peculiarities of thin-film cells.

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